

# From Jet Counting to Jet Vetoes

Peter Schichtel<sup>1,\*</sup>, Christoph Englert<sup>2</sup>, Erik Gerwick<sup>3</sup>, Tilman Plehn<sup>1</sup>, Steffen Schumann<sup>3</sup>

<sup>1</sup> Institut für Theoretische Physik, Universität Heidelberg, Germany

<sup>2</sup> Institute for Particle Physics Phenomenology, Durham University, United Kingdom

<sup>3</sup> II. Physikalisches Institut, Universität Göttingen, Germany

\* *Speaker*

DOI: will be assigned

The properties of multi-jet events impact many LHC analysis. The exclusive number of jets at hadron colliders can be described in terms of two simple patterns: staircase scaling and Poisson scaling. In photon plus jets production we can interpolate between the two patterns using simple kinematic cuts. The associated theoretical errors are well under control. Understanding such exclusive jet multiplicities significantly impacts Higgs searches and searches for supersymmetry at the LHC.

## 1 Introduction

In LHC searches jets and their properties play an important role for our understanding of hadron collisions. Jets in association with  $W/Z$  bosons as well as pure QCD jets not only help us to understand the theory, but also pose important backgrounds to new physics searches. Currently, the Higgs searches are certainly the most exciting LHC analysis. In the weak boson fusion (WBF) channel these searches rely on central jet vetoes, where jet radiation between two hard tagging jets is forbidden [1]. This idea is based on the color structure in WBF processes. Nowadays, for example the  $H \rightarrow WW$  searches are divided into *exclusive* 0, 1 and 2 jet bins. Whenever new physics scenarios introduce new heavy colored particles [2] their search relies on jets which appear as decay and radiation jets. The production scale for such heavy objects is encoded in the effective mass  $m_{\text{eff}} = \not{p}_T + \sum_{\text{jets}} p_{T,\text{jet}}$ , which is essentially proportional to the number of jets.

We propose the *exclusive* number of jets  $n_{\text{jets}}$  as the proper observable to study jets at the LHC. If we control this observable we can in addition use many multi-jet observables, like  $m_{\text{eff}}$ , whose uncertainties are otherwise notorious. There are, however, some issues in the definition of *exclusive* as compared to *inclusive* multi-jet observables. To gain higher precision we usually rely on higher order calculations, which in QCD predict inclusive observables. This means that once we include parton densities obeying the DGLAP equation any number of collinear jets is automatically included. On the other hand, exclusive jet bins are statistically independent. We use SHERPA [3] and its CKKW [4] algorithm to generate matched LO events to study exclusive jet cross-section ratios. In general we observe two distinct patterns: Poisson and staircase scaling.

## 2 Scaling patterns

### 2.1 Poisson scaling

Poisson processes are well known for example when we rely on the eikonal approximation [5, 6]. There, the matrix element factorizes for example from soft photon emission

$$\mathcal{M}_{n+1} = g_s T^3 \epsilon_\mu^* \bar{u}(q) \frac{q^\mu + \mathcal{O}(\not{k})}{qk + \mathcal{O}(k^2)} \mathcal{M}_n . \quad (1)$$

This relation can be used to resum emissions to all orders. It leads to a Poisson distribution for visible emissions

$$\sigma_n \propto \frac{\bar{n}^n}{n!} e^{-\bar{n}} \quad \text{with} \quad \bar{n} \propto \frac{\alpha}{\pi} \log \frac{E_{\text{hard}}}{E_{\text{soft}}} . \quad (2)$$

The numerator is just the exponentiation of  $n$  emission probabilities, while the  $n!$  factor takes care of the bosonic phase space. The exponential factor normalizes the distribution correctly. This way we find the logarithmic dependence of  $\bar{n}$ , where  $E_{\text{soft}}$  is the minimum resolution for soft photons. The cross-section ratios for Poisson processes immediately follow as

$$R_{(n+1)/n} \equiv \frac{\sigma_{n+1}}{\sigma_n} = \frac{\bar{n}}{n+1} . \quad (3)$$

We observe this behavior in all QED processes in the soft limit.

### 2.2 Staircase scaling

In contrast to Eq.(3) we find constant values for QCD and  $W/Z$  plus jets at hadron colliders. This behavior is called staircase scaling and follows [7, 8]

$$R_{(n+1)/n} \equiv \frac{\sigma_{n+1}}{\sigma_n} = R . \quad (4)$$

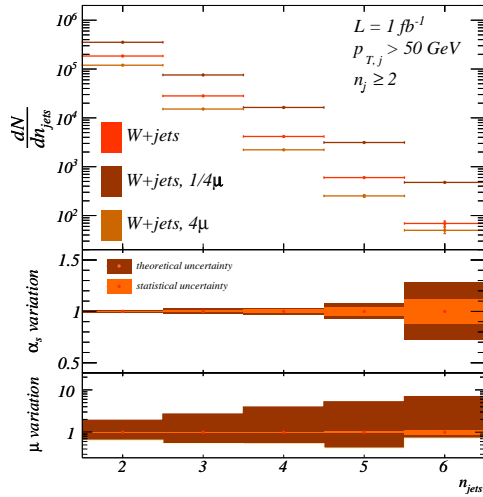


Figure 1: Theory uncertainties for  $W$  plus jets production. Figure from Ref.[7].

beyond the expected accuracy we can treat it as a MC tuning parameter, which happens to be close to unity for SHERPA [7].

Staircase scaling is a well established fact known since UA1 [8] and has been observed by ATLAS and CMS [9, 10]. Using SHERPA [3] we simulate exclusive  $n_{\text{jets}}$  rates for  $W/Z$  plus jets and for QCD jets up to  $n_{\text{jets}} = 8$  and reproduce this pattern. A major issue in the prediction of exclusive observables is the estimation of theoretical uncertainties. We rely on two handles: the value of the strong coupling  $\alpha_s(m_Z)$  and a free overall scale parameter connected to the factorization scale. The uncertainties we estimate by varying  $\alpha_s(m_Z)$  within its allowed values and by multiplying the default scale by 1/4 and 4. In Fig. 1 we show the  $n_{\text{jets}}$  distribution including uncertainties for  $W$  plus jets. While the variation of  $\alpha_s$  only gives a small error bar the impact of changing  $\mu$  is very large. However, the actual staircase pattern is not altered.

Interpreting the large scale variation as an effect beyond the expected accuracy we can treat it as a MC tuning parameter, which happens to be

### 3 Photon laboratory

The perfect place to study Poisson and staircase scaling in more detail is photon plus jets [11]. It has a high cross section and is therefore accessible for early LHC data. At first glance neither Poisson nor staircase scaling is observed in this channel. In contrast to the  $W/Z$  case the photon has no mass to define a hard process.

Inspired by the staircase pattern in  $W/Z$  plus jets we propose the following cut scenario: count only jets and isolated photons above  $p_T^{\min}$ , then impose a wide separation cut between the photon and all the counted jets either in terms of the invariant mass or equivalently in terms of  $R$ . In Fig. 2 we observe staircase scaling for values of  $R > 1.0$  and for invariant masses around 90 GeV, given  $p_T^{\min} = 50$  GeV.

To see Poisson scaling we induce a large logarithm as in Eq.(2) by asking for one jet with  $p_T > 100$  GeV and lowering  $p_T^{\min} = 20$  GeV. As we can see in Fig. 2 the cross section ratios follow a Poisson distribution. For high jet multiplicities the logarithm runs out of steam and we return to staircase scaling, with a constant ratio  $R$  determined by  $p_T^{\min} = 20$  GeV. The quantitative description of the staircase and Poisson scaling in the photon plus jets can be directly linked to the  $W/Z$  plus jets case [11].

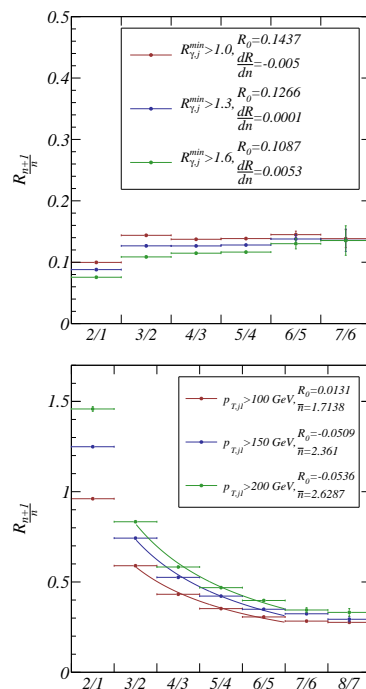


Figure 2: Kinematic regimes showing staircase and Poisson scaling. Figure from Ref. [11].

## 4 Applications

### 4.1 Higgs searches

In WBF Higgs searches we use a jet veto to suppress QCD backgrounds. The prediction of the jet veto probability is notorious [12]. In Fig. 3 we show how the WBF cuts drive the backgrounds into the Poisson regime while the signal stays approximately staircase. A simple fit to the  $n_{\text{jets}}$  distribution gives the veto survival probability.

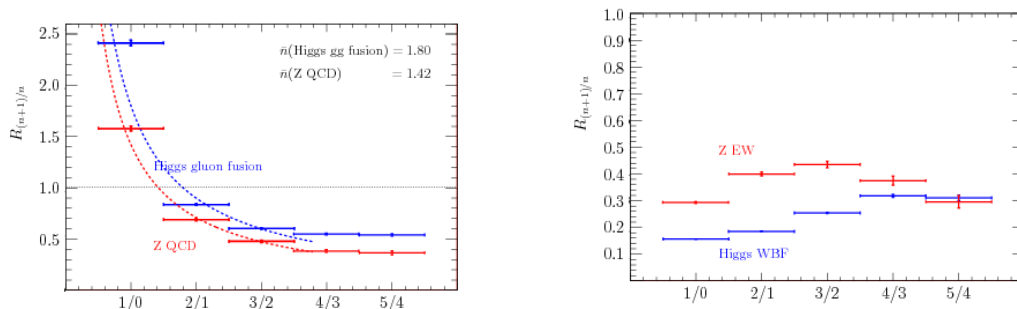


Figure 3: Poisson backgrounds (left) and staircase signal (right) for Higgs production. Figure from Ref. [12].

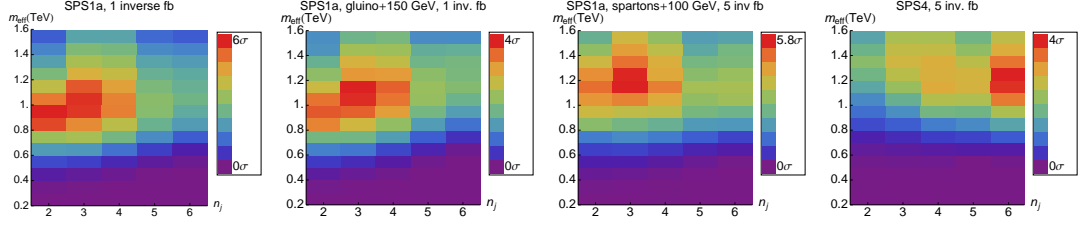


Figure 4: Two-dimensional likelihood for an SPS1a and SPS4 SUSY signal over backgrounds. Figure from Ref. [7].

## 4.2 Inclusive searches and autofocus

Searches for new physics focus on heavy colored states, for example decaying to dark matter. Contrary to tuned cuts searches, which rely on model spectra, we propose an inclusive ansatz, where we only count jets and apply a missing energy cut [7]. Information about the heavy mass scale is encoded in the effective mass. Due to its close connection to  $n_{\text{jets}}$  this mass observable is well controlled and can be used in our analysis. It yields complementary information to the number of jets. While  $n_{\text{jets}}$  is sensitive to deviations mostly in the high multiplicity regime, the effective mass also is sensitive for low multiplicities.

For a simple supersymmetric spectrum we use both observables to perform a log-likelihood test of the SM and SUSY hypotheses. The two-dimensional likelihoods for the different squark and gluino channels we show in Fig. 4. While the  $m_{\text{eff}}$  axis reflects the mass of the pair of heavy new states, the  $n_{\text{jets}}$  axis is sensitive to the color charge of the squarks and gluinos.

## 5 Acknowledgments

P.S. acknowledges support by the International Max Planck Research School for Precision Tests of Fundamental Symmetries.

## References

- [1] D. L. Rainwater and D. Zeppenfeld. Phys.Rev. **D60** (1999) 113004, [arXiv:hep-ph/9906218](#) [hep-ph].
- [2] D. E. Morrissey, T. Plehn, and T. M. Tait. Phys.Rept. **515** (2012) 1–113, [arXiv:0912.3259](#) [hep-ph].
- [3] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, *et al.* JHEP **0902** (2009) 007, [arXiv:0811.4622](#) [hep-ph].
- [4] S. Catani, F. Krauss, R. Kuhn, and B. Webber. JHEP **0111** (2001) 063.
- [5] M. E. Peskin and D. V. Schroeder. Westview Press (1995) .
- [6] E. Laenen, L. Magnea, G. Stavenga, and C. D. White. JHEP **1101** (2011) 141, [arXiv:1010.1860](#) [hep-ph].
- [7] C. Englert, T. Plehn, P. Schichtel, and S. Schumann. Phys.Rev. **D83** (2011) 095009, [arXiv:1102.4615](#) [hep-ph].
- [8] S. Ellis, R. Kleiss, and W. J. Stirling. Phys.Lett. **B154** (1985) 435.
- [9] G. Aad *et al.* Phys.Lett. **B698** (2011) 325–345, [arXiv:1012.5382](#) [hep-ex].
- [10] CMS-PAS-EWK-10-012 (2011) .
- [11] C. Englert, T. Plehn, P. Schichtel, and S. Schumann. JHEP **1202** (2012) 030, [arXiv:1108.5473](#) [hep-ph].
- [12] E. Gerwick, T. Plehn, and S. Schumann. Phys.Rev.Lett. **108** (2012) 032003, [arXiv:1108.3335](#) [hep-ph].